Precision measurement of the electric quadrupole moment of ^{31}Al

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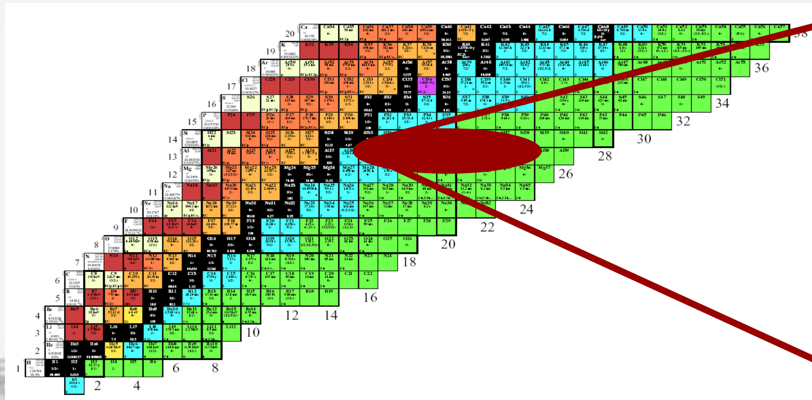
Overview

- Physics motivation
- The experimental set-up
- The β-NMR technique and the Larmor frequency of ^{31}Al
- The β-NQR technique and the quadrupole moment of ^{31}Al
- Interpretation of the results
- Conclusions

Physics motivation

1. Nuclei under study: the neutron rich Al-isotopes …



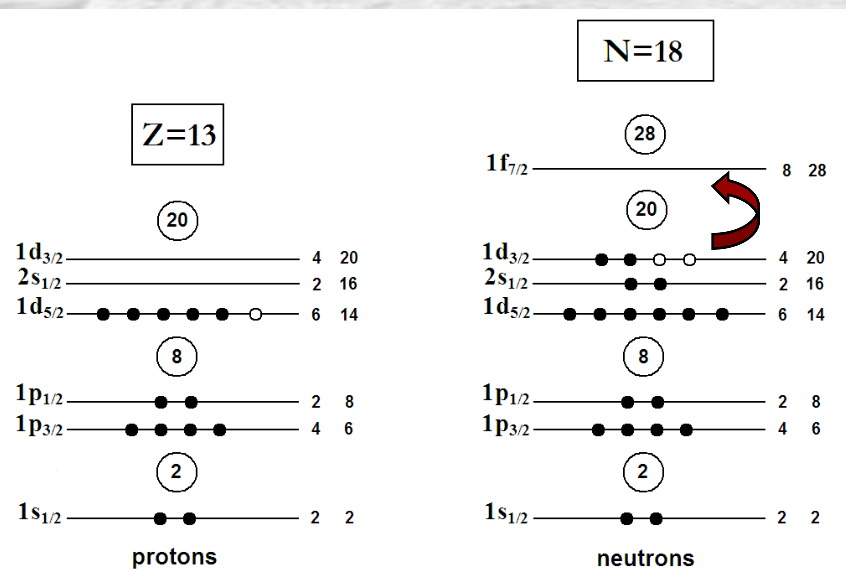
In particular: ^{31}Al

13 protons and 18 neutrons

- 1 valence proton hole in $1d_{5/2}$
- 2 valence neutrons in $1d_{3/2}$

Important step towards magic ^{33}Al

2. … at the border of the island of inversion



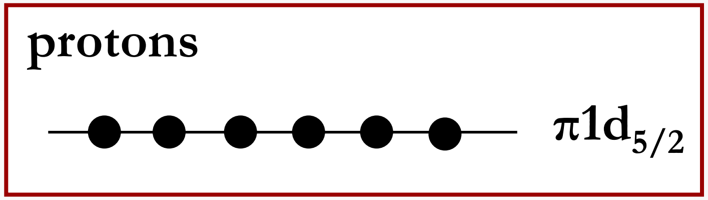
The island of inversion: what?

Region of Ne, Na and Mg isotopes with neutron number N=20-22, characterized by the dominance of neutron excitations from the sd to the pf-orbits in the ground state.

Neutron excitations in Al-isotopes?

The island of inversion: why?

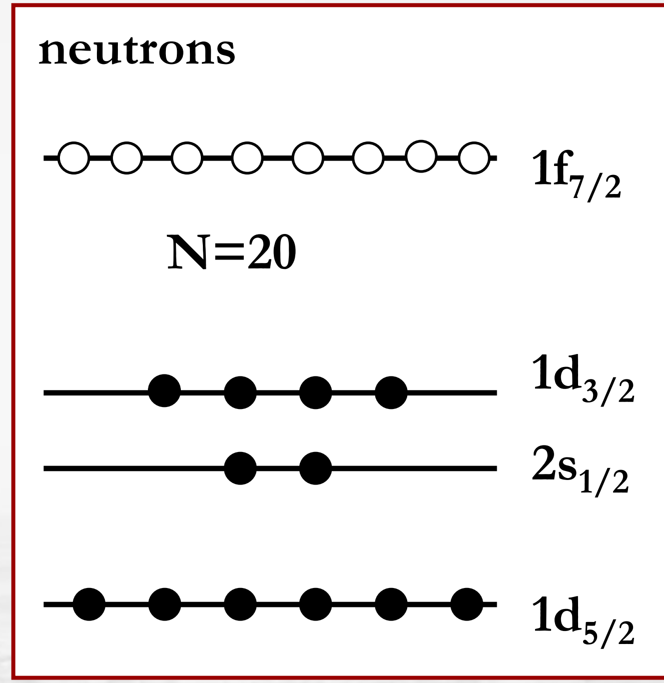
VANISHING OF THE N=20 SHELL CLOSURE



The tensor force part in the nucleon-nucleon interaction [1]
* (l+1/2) and (l'-1/2) orbitals attract each other
* (l+1/2) and (l'+1/2) orbitals repel each other

Strong attraction between $\pi d_{5/2}$ and $\nu d_{3/2}$ decreases when protons are taken away from $\pi d_{5/2}$ [2]

Mild repulsion between $\pi d_{5/2}$ and $\nu f_{7/2}$ also decreases when protons are taken away from $\pi d_{5/2}$ [2]



[1] Otsuka et.al. PRL 87 (2001) 082502
[2] Sorlin et.al. Prog. Part. Nucl. Phys. 61 (2008) 602

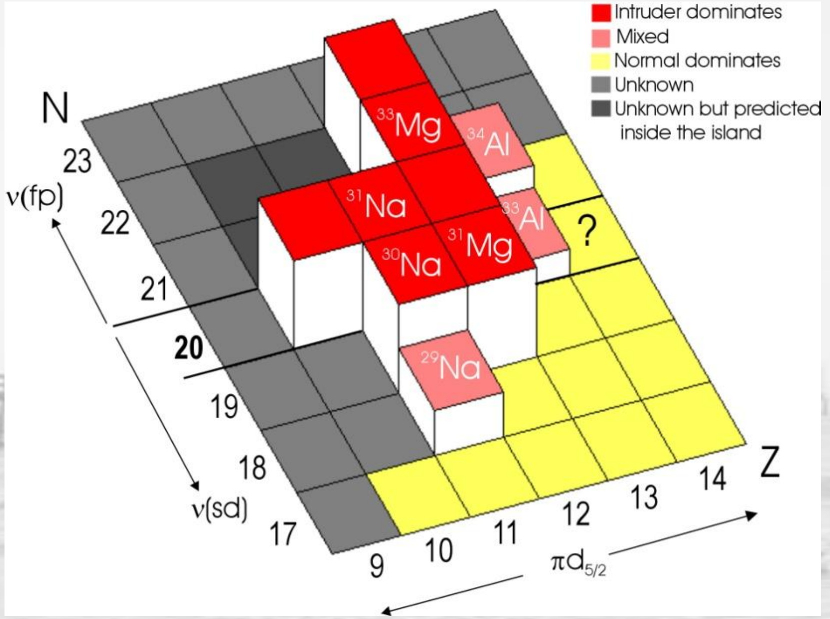
NEUTRON EXCITATIONS ACROSS N=20 DOMINATE

when the energy loss due to promotion of 2 neutrons across N=20 is compensated by the gain in **correlation energy** obtained from 2p-2h excitations [Caurier et al., PRC 59 (1998) 2033]

⇒ Mainly from quadrupole terms in π-ν and ν-ν interaction [Heyde et al. J. Phys.G 17 (1991) 135]

The island of inversion: experiments

EARLIER EXPERIMENTAL EVIDENCE



- S_{2n}- values for $^{26\text{-}32}$Na

  [Thibault et al. PRC 12 (1975) 644]

- low lying 2+ state in ^{32}Mg
  deformed ground state

  [D'etraz et al. PRC 19 (1979) 164, Guillemaud et al. NPA 426 (1984) 37]

- Anomalous B(E2) values and nuclear moments of neutron-rich Ne, Na and Mg isotopes

  [Pritychenko et al. PLB 461 (1999) 322]
  [Keim et al. Eur. Phys. J. A 8 (2000) 31]
  [Neyens et al. PRL 94 (2005) 022501]

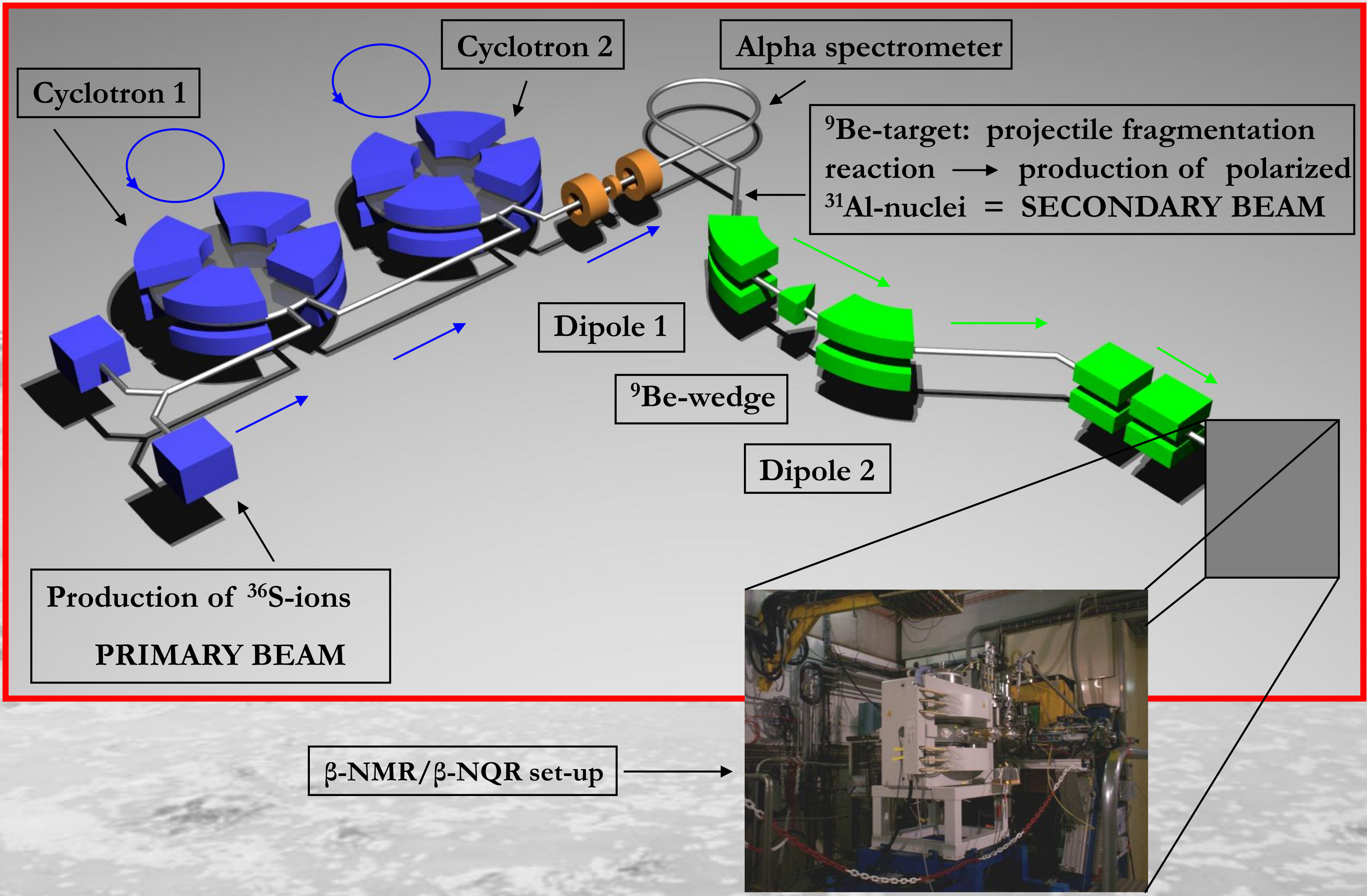
AT THE BORDER OF THE ISLAND OF INVERSION: Al

From magnetic moment measurements : $^{31\text{-}32}$Al are normal sd-shell nuclei
$^{33\text{-}34}$Al intruder configurations present

Himpe et al. PLB 643 (2006) 257, PLB 658 (2008) 203
Ueno et al. PLB 615 (2005) 186

➡ **Check these conclusions by measuring the quadrupole moment**
Improve earlier measurement Q(^{31}Al) = 112(32) mb [Nagae et al. PRC 79 (2009) 027301]

Experimental setup: GANIL-LISE



Experimental setup: β-NMR/β-NQR

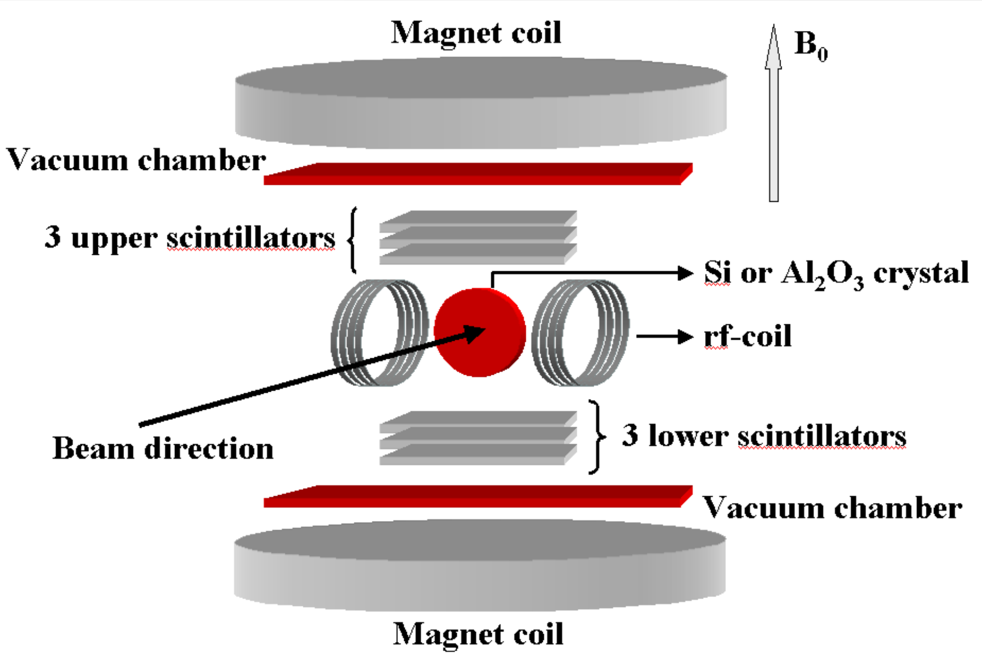
1. **^{31}Al nuclei in β-NMR/ β-NQR setup**

Polarized ^{31}Al nuclei are **implanted** in

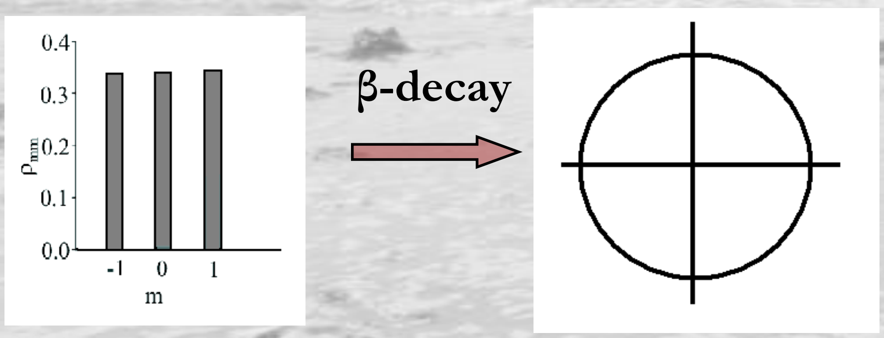
- cubic Si-crystal for β-NMR
- Al_2O_3 crystal with axial symmetric electric field gradient for β-NQR

β-decay registered by 2x3 detectors

Static **magnetic field** B_0

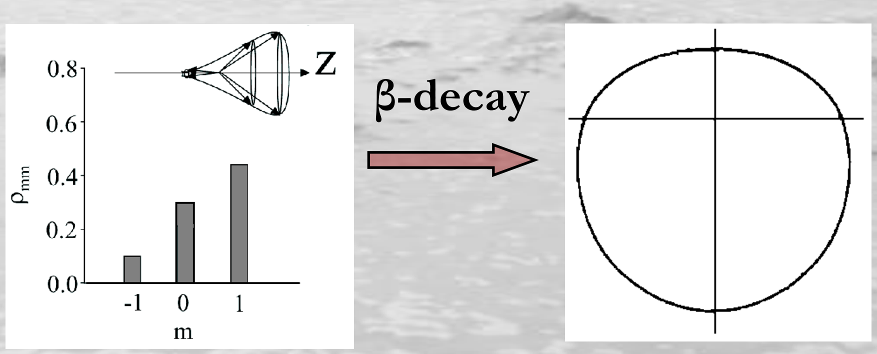


2. **Polarized nuclei and their β-decay**



isotropic

$N_{up}/N_{down}=1$

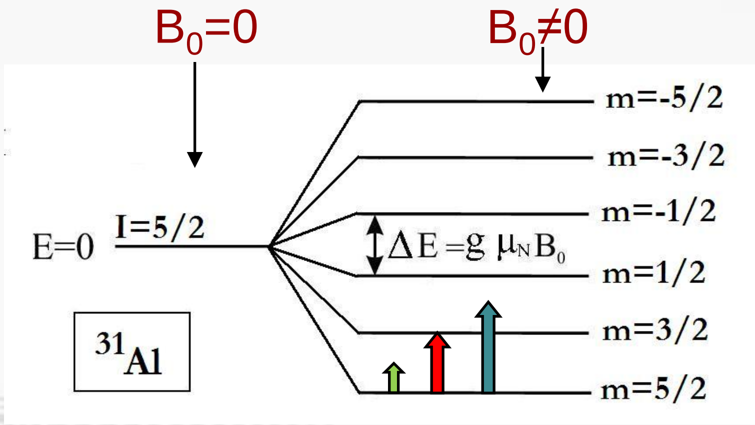


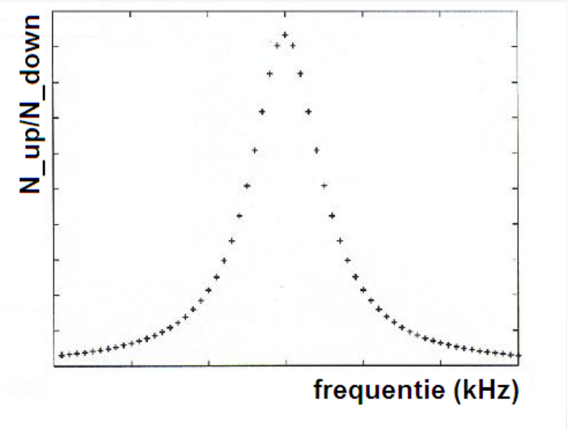
polarized

$N_{up}/N_{down}\neq1$

β-NMR technique and Larmor frequency of ^{31}Al

✓ Nucleus in an external magnetic field ⟶ Zeemansplitting of the nuclear levels





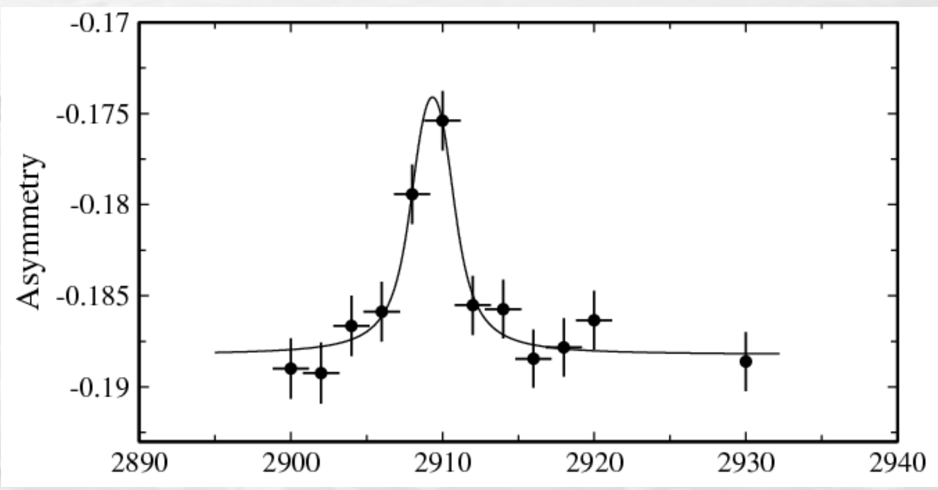
✓ Apply a radio frequent field with energy hν ⟶ resonance when $h\nu_L = g\mu_N B_0$

Use **modulation** to reach intermediate frequencies…

✓ ^{31}Al **β-NMR result** in Si crystal

B_0 = 0.25 Tesla
g=1.532(2) [Himpe PLB 643(2006)257]
frequency modulation = 1.2 kHz

$\upsilon_L(^{31}\mathrm{Al})$ = 2909.3(2) kHz



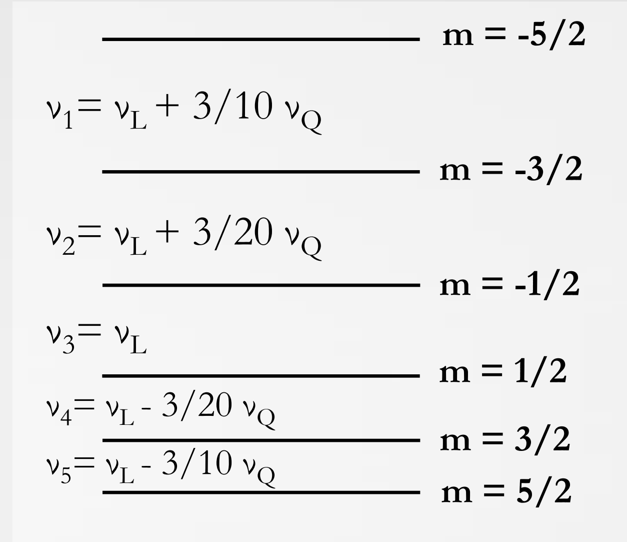
β-NQR technique and Q(^{31}Al)

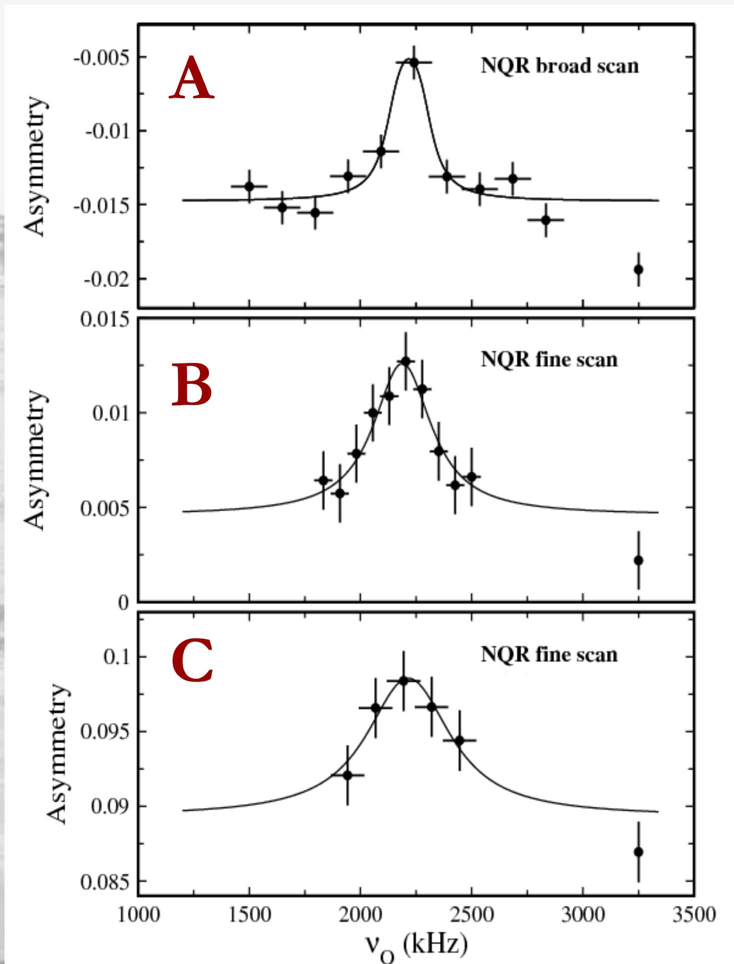
^{31}Al implanted in Al_2O_3, electric field gradient present

→ non-equidistant level splitting, 5 transition freq.

ν_L = 2909.3(2) kHz
$\nu_Q = eQV_{zz}/h$

Scan as a function of $\nu_Q \sim Q$





A : ν_Q = 2218(75) kHz
B : ν_Q = 2188(25) kHz
C : ν_Q = 2215(47) kHz

Weighted mean:
ν_Q = 2196(21) kHz

Calculate the quadrupole moment Q(^{31}Al) relative to the one of ^{27}Al:

[Kellö et al. Chem. Phys. Lett. 304 (1999) 414]
[Filsinger et al. J.Magn.Res. 125 (1997) 280]

$$|Q(^{31}Al)| = \{|Q(^{27}Al)|\,\nu_Q(^{31}Al)\}/\nu_Q(^{27}Al)$$

|Q(^{31}Al)| = 134.0(16) mb

Interpretation of the results

1. Interpretation using the effective charges e_p=1.3e and e_n=0.5e

Use **shell-model calculations** to reproduce the experimental quadrupole moments

- ANTOINE – sdpf [Nummela, PRC 63 (2001) 044316]
- Monte Carlo Shell Model – SDPF-M [Utsuno, PRC 70 (2004) 044307]

Protons restricted to sd-orbitals

Neutrons: - restricted to sd-orbitals (sdpf) □

- forced to have 2 in $f_{7/2}$ and $p_{3/2}$ (sdpf) △
- free in $sdf_{7/2}p_{3/2}$ (sdpf) ◇
- free in $sdf_{7/2}p_{3/2}$ (SDPF-M) *

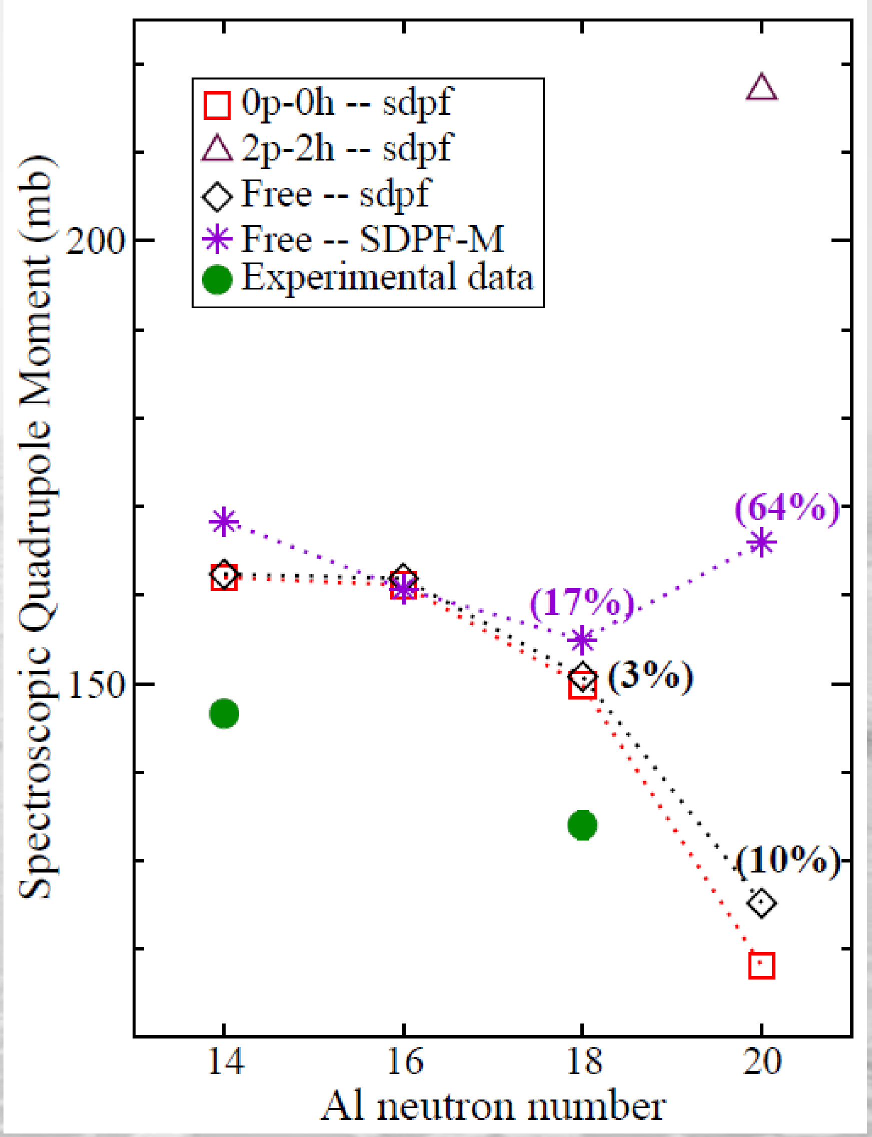
Use effective charges **e_p=1.3e and e_n=0.5e**
[Brown et al. Ann. Rev. Nucl. Part. Sci. 38 (1988) 29]

Shell model calculations with e_p=1.3 and e_n=0.5

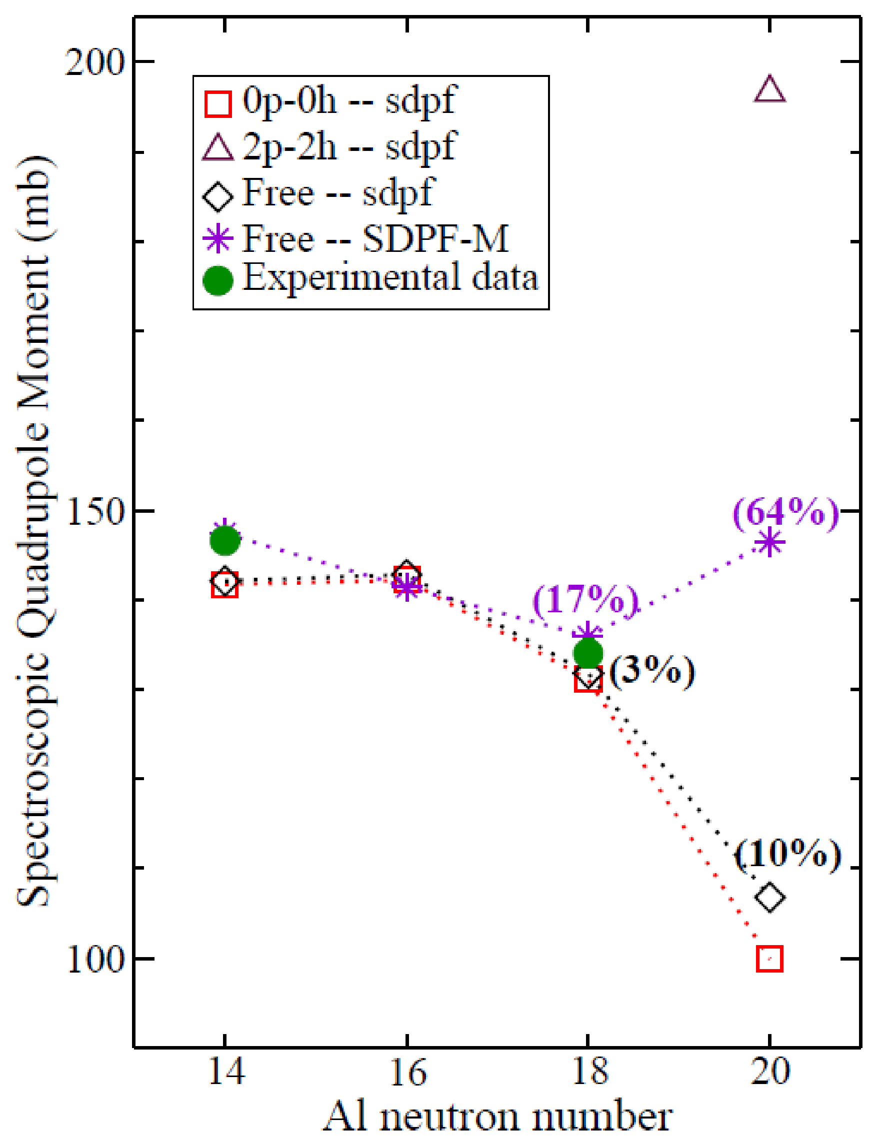
reproduce the trend

overestimate experiment with 15%

Rescale the proton effective charge in order to reproduce the experimental Q(^{27}Al): **e_p=1.1e**



2. Interpretation using the effective charges e_p=1.1e and e_n=0.5e



Use rescaled proton effective charge: **e_p=1.1e**

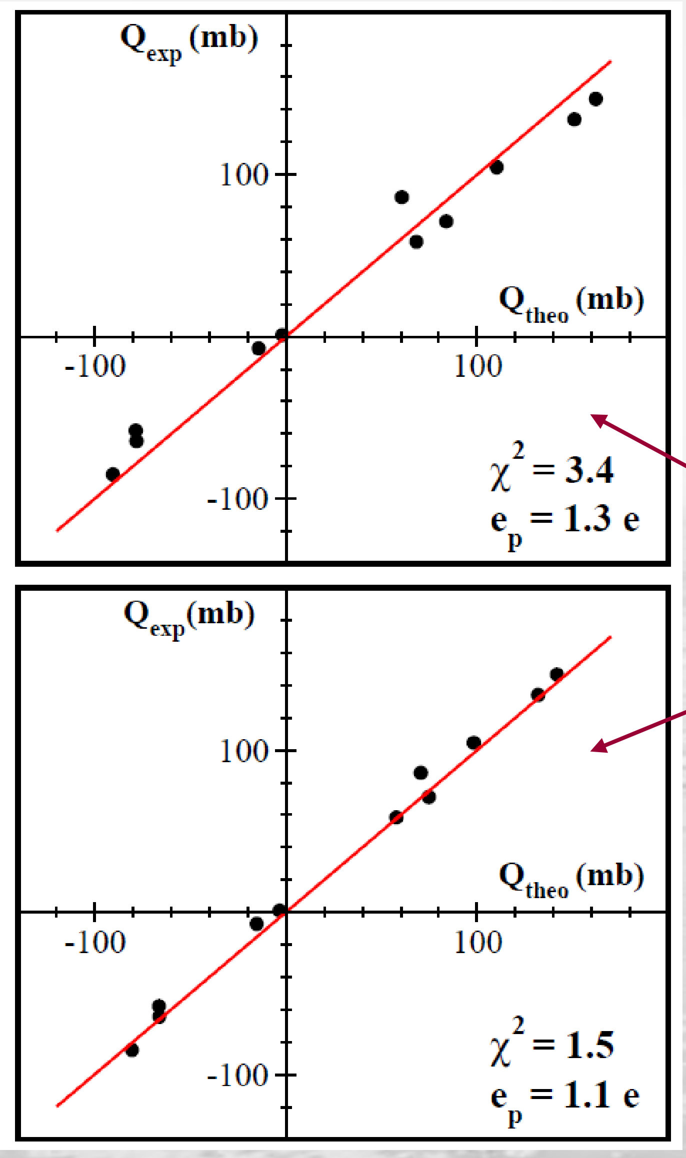
Are intruder configurations present in ^{31}Al ground state?

$^{27-29}$Al: normal sd-shell nuclei

^{31}Al: normal sd-configurations dominate possible small admixture (<20%) of intruder states

^{33}Al (N=20): in case of a pure sd ground state a strong decrease of Q compared to ^{31}Al is expected

3. Why using the effective charges e_p=1.1e and e_n=0.5e ?



The adopted proton charge e_p=1.3e was established in 1988 by Brown-Wildenthal [Brown, Ann. Rev. Nucl. Part. Sci. 38 (1988) 29]

e_p=1.3e still valid with more recent shell-model calculations and accurate experimental values?

Use - Calculations performed with ANTOINE (sdpf) protons in sd-shell and neutrons in $sdf_{7/2}p_{3/2}$

e_p = 1.3e

e_p = 1.1e

- Recent experimental Q-moments for odd Z – even N nuclei with protons in the sd-shell [Matsuta, J. Phys. Conf. Ser. 20 (2005) 169 and N.J. Stone, At. Data and Nucl. Data Tables 90 (2005) 75]

e_p = 1.1e is a more realistic effective proton charge for the proton sd-shell than e_p=1.3e

Conclusions

- What happens at the border of the island of inversion?
  Are intruder configurations present in the neutron-rich Al-isotopes?
- $|Q(^{31}Al)| = 134.0(16)$ mb, much more precise and in agreement with the previous measurement $|Q(^{31}Al)| = 112(32)$mb
- The ^{31}Al ground state is dominated by normal νsd-shell configurations. A small admixture (<20%) of 2p2h-intruder neutron states is possible.
- The Al-isotopes form a gradual transition from the island of inversion (Ne, Na, Mg) to the normal Si-isotopes
- e_p = 1.1e is a more realistic effective proton charge for the proton sd-shell than e_p=1.3e

The collaboration

4. Continuous Beam versus Adiabatic Fast Passage Method

The continuous beam technique

- Performed with a "continuous beam", nuclei are implanted continuously and the RF-sequence is sent continuously
- Drawback: the polarization is destroyed at resonance
- Advantage: "simple" technique

The adiabatic fast passage method

- Using a pulsed beam
  1 cycle = 1 sec beam on, 45 msec RF on, 1sec counting, 45 msec RF on
- Advantage: at resonance the polarization is inverted ⟹ double NMR-effect
- Drawback: difficult method with a lot a restricted parameters

The measured larmor frequency of ^{31}Al

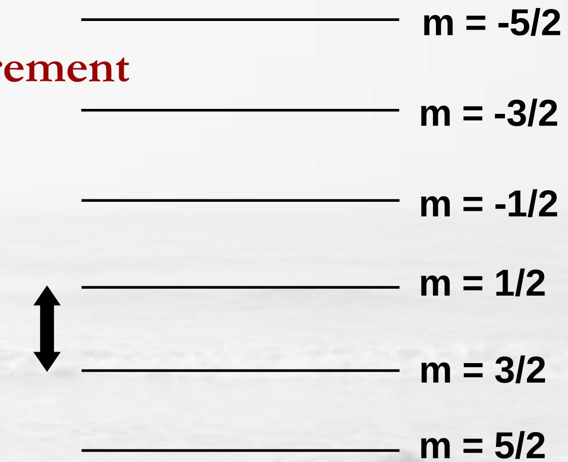
1. β-NMR on the ^{31}Al ground state

^{31}Al

- spin $5/2^{+}$
- known g-factor
  g=1.532(2) [1]
  [1] Himpe et al. PLB 643(2006)257
- half life $t_{1/2}$ = 644 ms
- Q_{β}=7.995(20) MeV

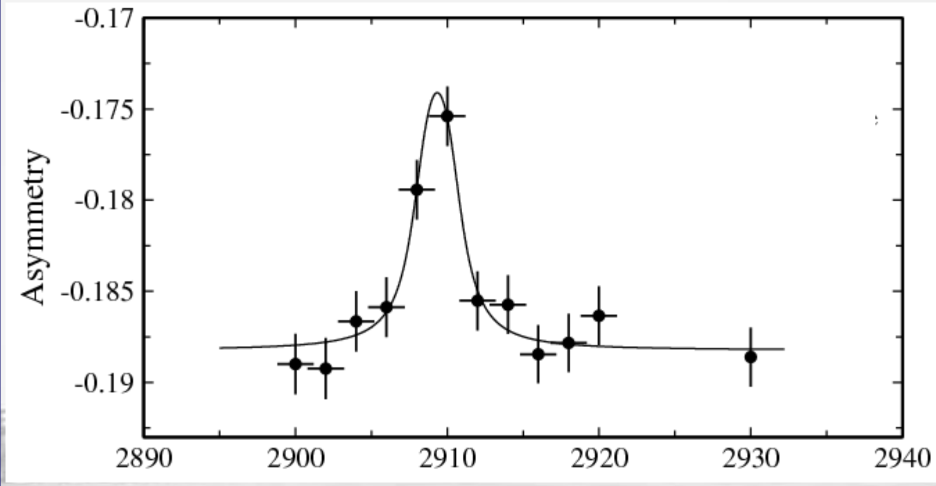
Precision measurement of the larmor frequency

$\nu_L = g\mu_N B_0/h$



β-NMR in Si-crystal (cubic lattice structure)
Equidistant level splitting
Transition frequency: $\nu_L = g\mu_N B_0/h$ with known g-factor

2. β-NMR results on ^{31}Al



Continuous beam technique

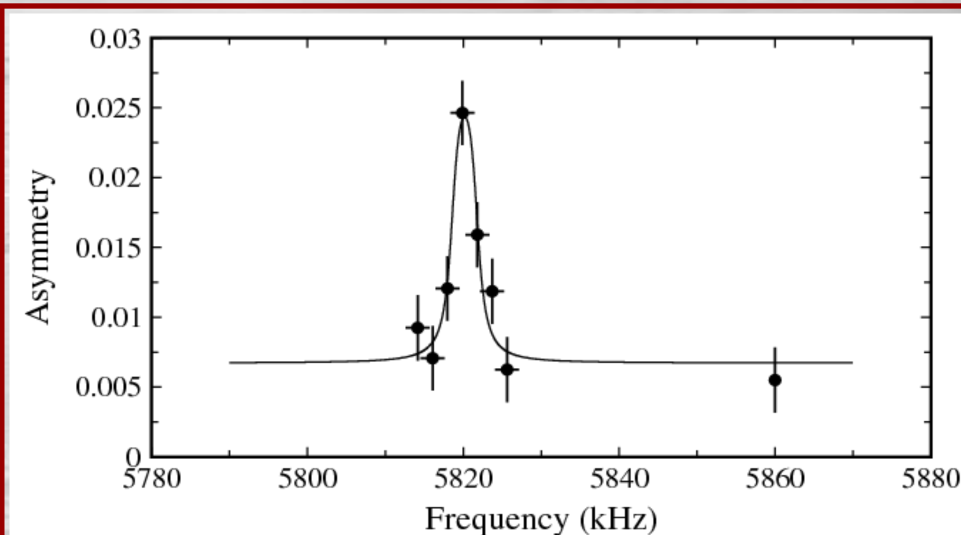
B_0 = 0.25 Tesla
g=1.532(2)
frequency modulation = 1.2 kHz

υ_L = 2909.3(2) kHz

Adiabatic Fast Passage

B_0 = 0.5 Tesla
g=1.532(2)
frequency modulation = 1.54 kHz

υ_L = 5820.2(3) kHz



2. β-NQR with the adiabatic fast passage technique

^{31}Al implanted in Al_2O_3, electric field gradient present

→ non-equidistant level splitting

Angle between B and electric field gradient: θ=90°

$\nu_L = 5820.2(3)$ kHz

$\nu_Q = eQV_{zz}/h$

Scan as a function of ν_Q ~ quadrupole moment

m = -5/2

$\nu_1 = \nu_L - 3/20\ \nu_Q + 9/1600\ (\nu_Q^2/\nu_L)$

m = -3/2

$\nu_2 = \nu_L - 3/40\ \nu_Q + 9/1280\ (\nu_Q^2/\nu_L)$

m = -1/2

$\nu_3 = \nu_L + 9/800\ (\nu_Q^2/\nu_L)$

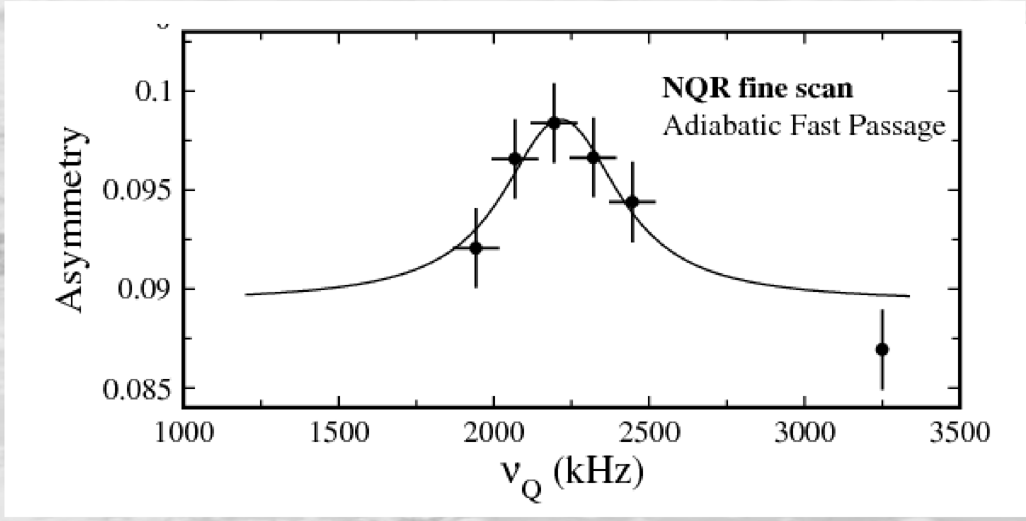
m = 1/2

$\nu_4 = \nu_L + 3/40\ \nu_Q - 9/1280\ (\nu_Q^2/\nu_L)$

m = 3/2

$\nu_5 = \nu_L + 3/20\ \nu_Q - 9/1600\ (\nu_Q^2/\nu_L)$

m = 5/2



NQR adiabatic fast passage:

ν_Q = 2217(45) kHz